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TECHNICAL NOTE

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NOTE ON THE THICKNESS OF THE HELIUM ION LAYER

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SUMMARY

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On the basis of recent experimental results as well as theoretical considerations of the temperature dependence of the light constituents (hydrogen and helium) in the upper atmosphere, a model of the helium ion belt – the "heliosphere" – is constructed. The thickness of the helium ion layer varies significantly with atmospheric temperature: about 2000 km at 1600°K and only about 200 km at 600°K. Correspondingly, charged particle profiles in the topside ionosphere may show a slope corresponding to He^{+} at high temperature, but not at low temperatures when the thickness of the helium ion layer is comparable to or less than the scale height of helium ions.

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Experimental evidence, in accordance with Nicolet's suggestion (Reference 1), for the presence of helium ions in the upper atmosphere, is now available from ion and electron density profiles (References 2 and 3), ion probe retarding potential experiments (References 4 and 5) and direct measurements with an RF ion spectrometer (Reference 6). Hanson (Reference 2), who first inferred the presence of He^+ from an experimental ion-density profile obtained by Hale (Reference 7), has called the layer of ionized helium the "heliosphere". In his analysis of Hale's data, Hanson concluded that the thickness of the helium ion layer, extending from 1200 km to about 3400 km, is of the order of 2000 km and that the measured scale height for helium ions corresponded to an atmospheric temperature of 1600°K.

Because of the presence of He^+, the upper ionosphere has to be considered a ternary ion mixture (0^+, He^+ and H^+). Although the diffusive equilibrium distribution of a minor ion species in an ion mixture is influenced by the other constituents – unlike neutral ones, because of the electric field resulting from the slight charge separation between electrons and positive ions (References 8 through 11), the relative concentrations of ionic species behave like neutral constituents (Reference 10). The boundaries of a region where an ionic species predominates can be defined by the transition or equal-concentration levels, i.e. the levels where the concentration of this species is equal to that of the neighboring ionic species.

The equal-concentration level h_{ij} can be expressed in terms of the geopotential height parameter (Reference 12):

$$z_{ij}' = H_{ij} \ln \eta_{ij} , \tag{1}$$

where $z_{ij}' = h_{ij}' - h_0'$ is the geopotential distance between the equal-concentration level and the reference level h_0' at which $[X_i^+]/[X_j^+] = \eta_{ij}$, and $H_{ij} = kT/(m_i - m_j)\, g_0$ with k the Boltzmann constant, T the absolute temperature, m_i and m_j the masses of the ionic species X_i and X_j and g_0 the acceleration of

*The material contained in this report also appeared in *Nature*, January 5, 1963, under the title, "Helium Ion Belt in the Upper Atmosphere."

gravity at the earth's surface. The geopotential altitude h' is related to the geometric altitude h by

$$h' = \int_0^h \frac{g(h)}{g_0}\, dh .$$

In this discussion the subscripts 1, 2 and 3 will refer to 0^+, He^+ and H^+, respectively.

The actual situation is complicated by the fact that the relative ion concentrations at the reference level η_{ij} are also functions of temperature. This is particularly true for the ratio η_{31} since the neutral hydrogen concentration at a constant altitude depends upon its escape rate from the upper atmosphere. Since this rate increases with temperature, the concentration of hydrogen at a constant level *increases* with *decreasing* temperature. The ratio $[H]/[0]$ at an altitude of 500 km (which we shall adopt as reference level h_0) increases by a factor of 100 for a temperature decrease from 2000 to 1000°K (References 13 and 14). If the proton concentration is governed by the charge exchange equilibrium condition (References 13 and 15), the ratio η_{31} varies with temperature in the same proportion as the ratio of the neutral constituents. The same argument applies if the protons are a result of photo-ionization rather than charge exchange. Similarly, a proportional variation of $[He]/[0]$ and η_{21} with temperature can be assumed. The helium concentration at 500 km varies only slightly with temperature (Reference 14) so that the ratio η_{21} will not vary as strongly as η_{31} with temperature.

For the present model the following values have been adopted: The concentration ratio $[H^+]/[0^+]$ at 500 km varies from $\eta_{31} = 10^{-4}$ at 1600°K to $\eta_{31} = 10^{-2}$ at 600°K; and the ratio $[He^+]/[0^+]$ at 500 km varies from $\eta_{21} = 5 \times 10^{-3}$ at 1600°K to $\eta_{21} = 5 \times 10^{-2}$ at 600°K. The temperature range corresponds to the extremes at the present level of solar activity. The chosen variation with temperature of η_{31} is in good agreement with Bates and Patterson (Reference 13), and that for η_{21} is consistent with the variation of the helium concentration of Nicolet and Kockarts (Reference 14).

Figure 1 shows the h_{12} and h_{23} transition levels, where $[He^+] = [0^+]$ and $[H^+] = [He^+]$ respectively, as a function of atmospheric temperature for the assumed variation of η_{ij} at 500 km, the reference level. The altitude difference $h_{23} - h_{12}$ between the two equal-concentration levels may be called the thickness τ of the helium ion layer. It is obvious that this thickness is drastically reduced as the temperature decreases. This possibility has previously been pointed out for the case where η_{ij} is constant (References 12 and 16).*

If the thickness τ is less than the local scale height for helium ions, $\tau < H(He^+)$; i.e., if the two equal-concentration levels h_{12} and h_{23} occur within one scale height, no distinct slope corresponding to He^+ will be distinguishable in an ion or electron density profile. This is the case for temperatures of the order of 1000°K or less. Figure 2 which presents normalized charged particle density profiles based on a ternary ion mixture for 800, 1000 and 1300°K and the corresponding η_{ij} versus the geopotential distance z' above the reference level, illustrates the fact that identification of helium ions

*From the final analysis of a recent ion density profile (Reference 5) it appears, that the equal-concentration levels at the corresponding temperature of 800°K are about 200 km lower than indicated in Figure 1, while the thickness of the helium ion layer is in good agreement with the present model. This fact seems to imply an even stronger temperature-dependence of the ion concentration ratios η_{ij} than was assumed here.

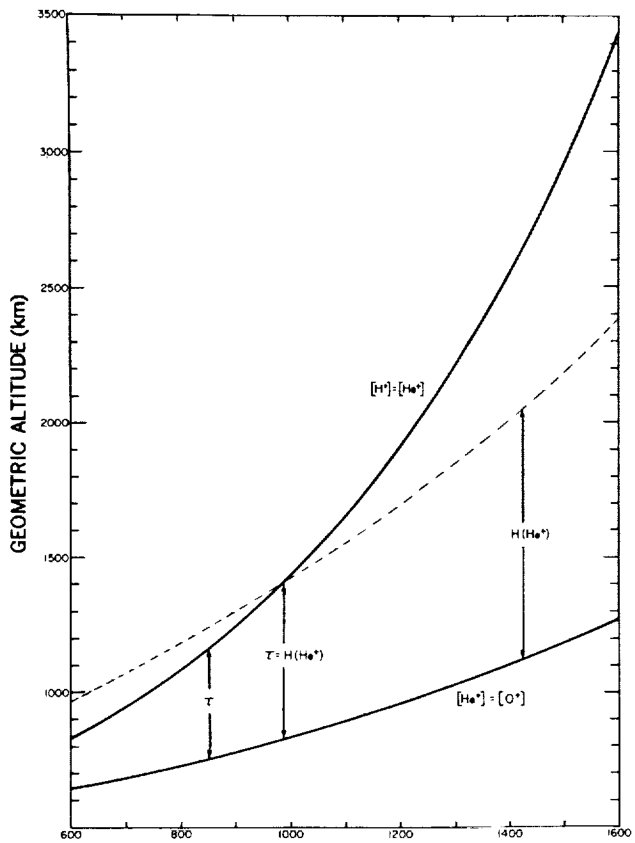

Figure 1—Equal concentration levels $[He^+] = [O^+]$ and $[H^+] = [He^+]$ on a geometric altitude scale versus atmospheric temperature. τ represents the thickness of the helium ion layer; the local scale height for He^+ is indicated by the distance between the dashed curve and the $[He^+] = [O^+]$ curve. The equal-concentration levels are based on the temperature-dependent ion concentration ratios η_{ij} at 500 km given in the text.

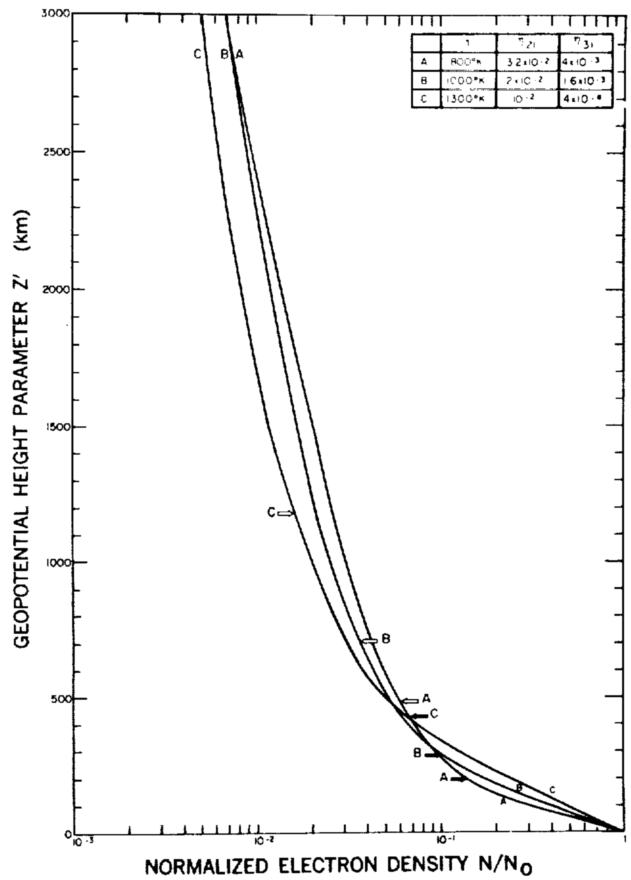

Figure 2—Normalized charged particle density profiles for a ternary ion-mixture corresponding to the listed ion concentration ratios η_{ij} and atmospheric temperatures as a function of geopotential distance z' above the reference level. The solid arrows indicate the equal concentration level $[He^+] = [O^+]$ and the open arrows $[H^+] = [He^+]$.

from profiles is virtually impossible for low temperatures. The profiles shown in Figure 2 were computed from the following formula (Reference 12):

$$N(z') = N_0 \exp\left(-\frac{1}{2}\left\{\left(\frac{z'}{H_1}\right) - \ln\left[1 + \eta_{21} \exp\left(\frac{z'}{H_{12}}\right) + \eta_{31} \exp\left(\frac{z'}{H_{13}}\right)\right] + \ln\left(1 + \eta_{21} + \eta_{31}\right)\right\}\right), \tag{2}$$

where N and N_0 are the electron (or total ion) density at z' and at the reference level $z' = 0$ respectively and all other symbols have their previously defined meaning.

A recent nighttime electron density profile reported by Ulwick and Pfister (Reference 17), failed to show evidence for the presence of He^+. In the light of the foregoing discussion, failure to detect He^+ from a profile does not prove the absence of He^+ but can be explained by the fact that the thickness of the helium ion layer at that time was comparable in magnitude to the scale height of He^+.

In fact, with an ion trap, Donley (Reference 5) recently obtained a nighttime ion density profile from which the presence of helium ions is not obvious. However, a preliminary retarding potential analysis of the same data indicates the presence of all three ionic constituents (0^+, He^+ and H^+). The combined ion density and composition data are consistent with the concept of a thin helium ion layer at low atmospheric temperatures.

Most recently, measurements of ion composition and temperature on the Ariel satellite (1962 ο1) provide additional evidence for the variation of thickness in the helium ion layer (Reference 18). It is expected that these experimental data will allow further refinements of the model concept presented here.

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